



US009053439B2

(12) **United States Patent**
Marwah et al.

(10) **Patent No.:** **US 9,053,439 B2**
(45) **Date of Patent:** **Jun. 9, 2015**

(54) **PREDICTING NEAR-FUTURE PHOTOVOLTAIC GENERATION**
(71) Applicant: **HEWLETT-PACKARD DEVELOPMENT COMPANY, L.P.**, Houston, TX (US)
(72) Inventors: **Manish Marwah**, Palo Alto, CA (US); **Martin Arlitt**, Calgary (CA); **Prithwish Chakraborty**, Blacksburg, VA (US); **Naren Ramakrishnan**, Blacksburg, VA (US)
(73) Assignee: **Hewlett-Packard Development Company, L.P.**, Houston, TX (US)
(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 274 days.

USPC 700/83, 86, 94, 295, 87, 18, 17, 24, 25, 700/65, 66; 702/3; 307/46, 47; 348/E7.061; 370/218, 355; 380/201, 252; 381/73.1; 386/E5.004, E5.043; 709/200, 201, 709/202, 223, 227; 715/716, 719, 727, 810, 715/840, 841; 718/102; 719/318; 725/116, 725/19, 20, 37, 41
See application file for complete search history.

(21) Appl. No.: **13/631,480**
(22) Filed: **Sep. 28, 2012**

(56) **References Cited**
U.S. PATENT DOCUMENTS
7,957,846 B2 6/2011 Hakim et al.
8,095,488 B1 * 1/2012 Satish et al. 706/20
(Continued)

(65) **Prior Publication Data**
US 2014/0095076 A1 Apr. 3, 2014

OTHER PUBLICATIONS
Phu et al., Motif-Based for Initialization the K-Means Clustering for Time Series Data, 2011, Springer-Verlag Berlin Heidelberg, pp. 11-20.*
(Continued)

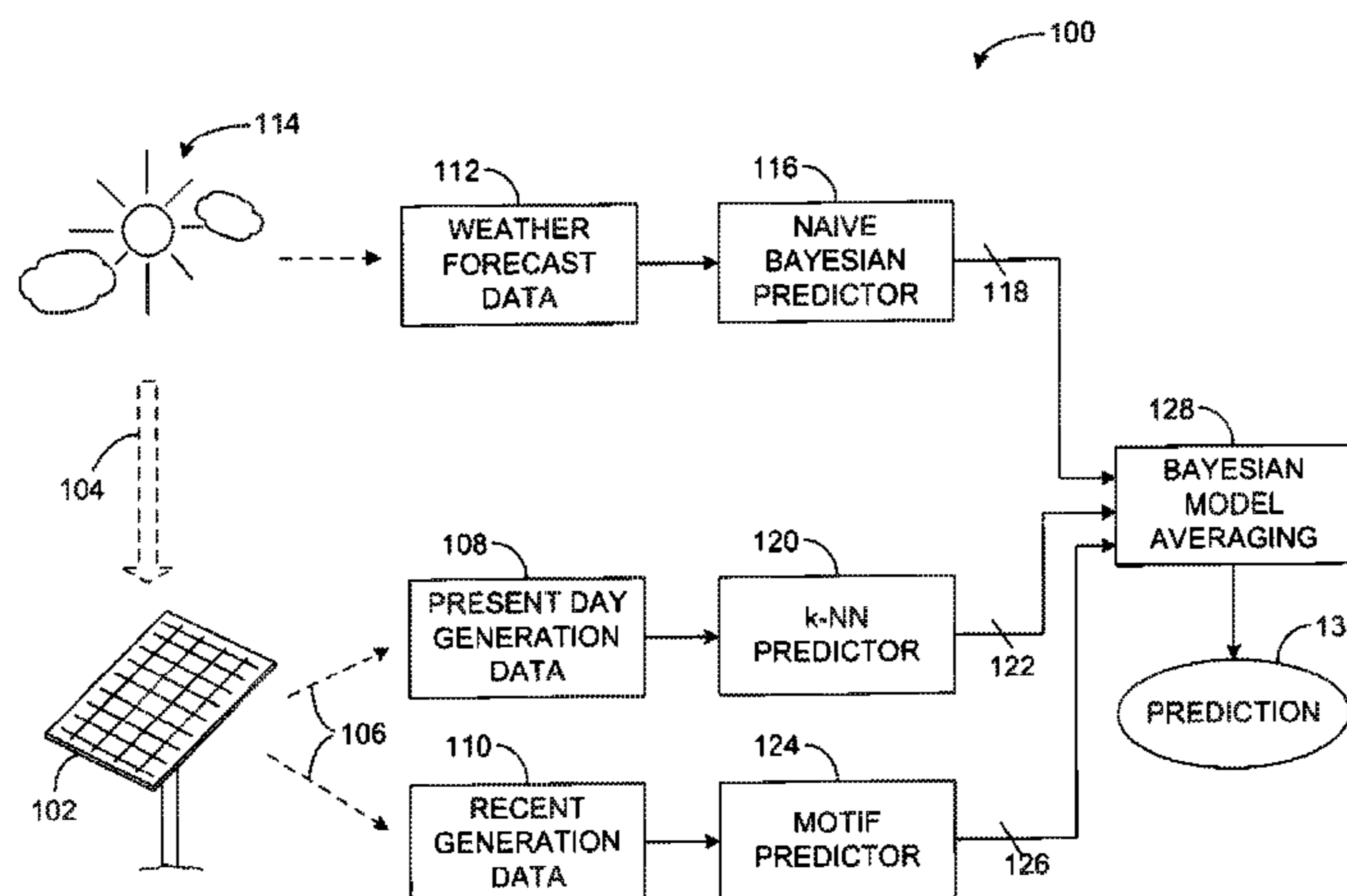
(51) **Int. Cl.**
G01W 1/00 (2006.01)
G06Q 10/04 (2012.01)
(52) **U.S. Cl.**
CPC **G06Q 10/04** (2013.01); **F24J 2200/04** (2013.01)

Primary Examiner — Mischita Henson
Assistant Examiner — Lisa Peters
(74) *Attorney, Agent, or Firm* — Hewlett-Packard Patent Department

(58) **Field of Classification Search**
CPC G06K 9/00369; G06K 9/62; G05B 15/02; G05B 19/042; G05B 2219/25323; G05B 2219/2613; G05B 2219/2615; G05B 2219/34038; G05B 19/0426; G05B 2219/23021; G05B 2219/23026; H04N 21/44222; H04N 21/4318; H04N 21/44008; H04N 21/4668; H04N 21/475; H04N 7/163; H04N 2005/91328; H04N 2005/91364; H04N 21/4131; H04N 21/42201; H04N 21/4532; H04N 21/47; H04N 5/782; H04N 5/913; G06F 3/0481; G06F 3/0482; G06N 5/025; G06Q 30/02; G06Q 30/0248; G06Q 30/0255; G06Q 30/0267; G06Q 30/0269; G06Q 30/0273

(57) **ABSTRACT**
Systems and automated methods for predicting photovoltaic (PV) generation are provided. Weather forecast data and present-day and historical PV generation data are provided to respective predictors. The predictors derive weighted predictions that are used to calculate a Bayesian model average. Near-future generation by the PV system is predicted using the Bayesian model average. Production rates, worker scheduling, hours of operation and other planning decisions can be made in accordance with the predicted near-future generation.

19 Claims, 7 Drawing Sheets



(56)

References Cited

U.S. PATENT DOCUMENTS

2007/0005419 A1* 1/2007 Horvitz et al. 705/14
2010/0231045 A1* 9/2010 Collins et al. 307/47
2012/0166085 A1* 6/2012 Gevorkian 702/3
2013/0054603 A1* 2/2013 Birdwell et al. 707/738

OTHER PUBLICATIONS

Chakraborty et al., Fine-grained Photovoltaic Output Prediction using a Bayesian Ensemble, 2012, Assoc for the Advancement of AI.*

Aksanli, et al. Utilizing Green Energy Prediction to Schedule Mixed Batch and Service Jobs in Data Centers.

Bianchini. Leveraging Renewable Energy in Data Centers: Present and Future.

Chakraborty, et al. Fine-grained Photovoltaic Output Prediction using a Bayesian Ensemble. Dept of Computer Science, Virginia Tech, Blacksburg, VA.

* cited by examiner

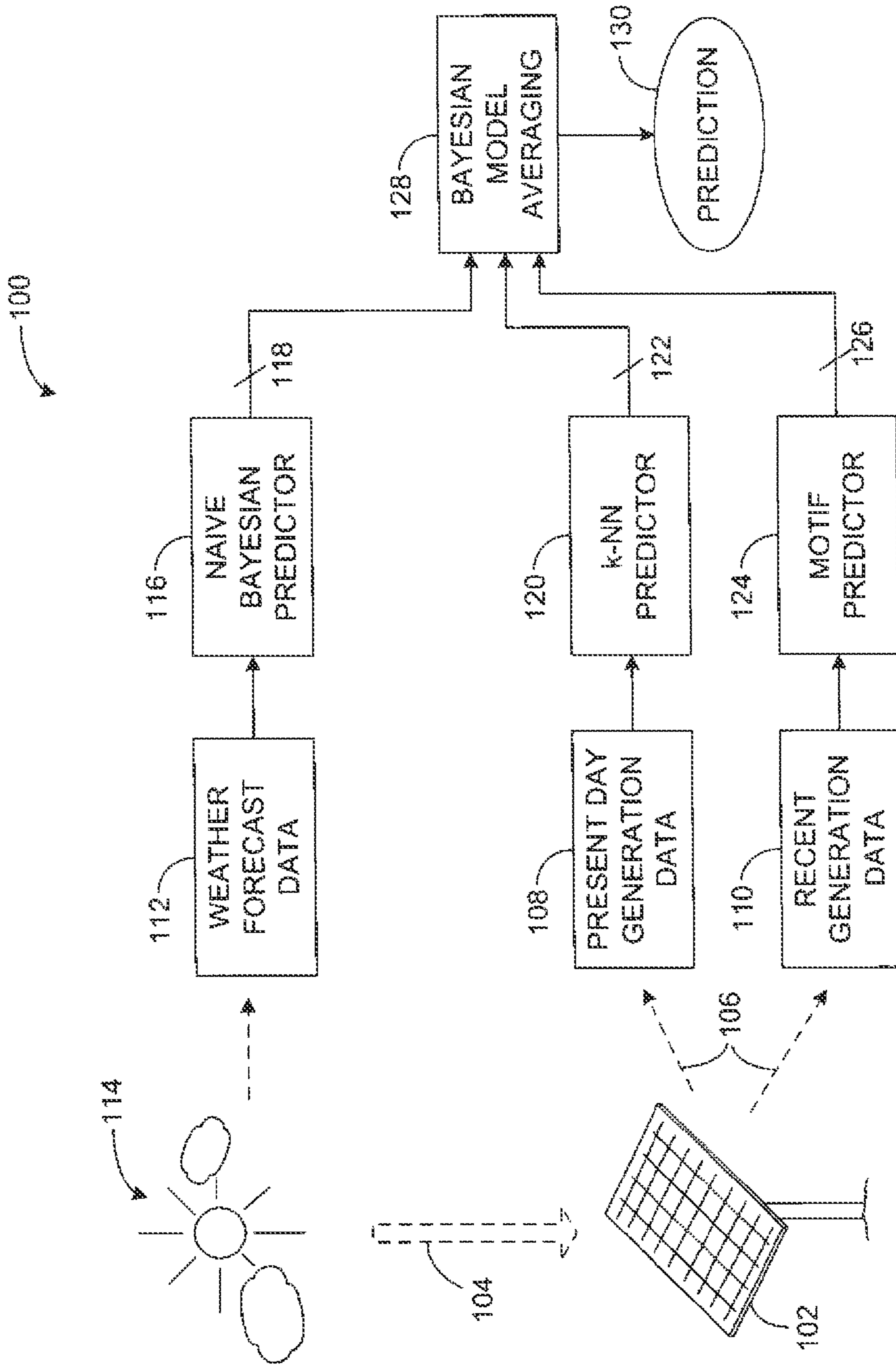


FIG. 1

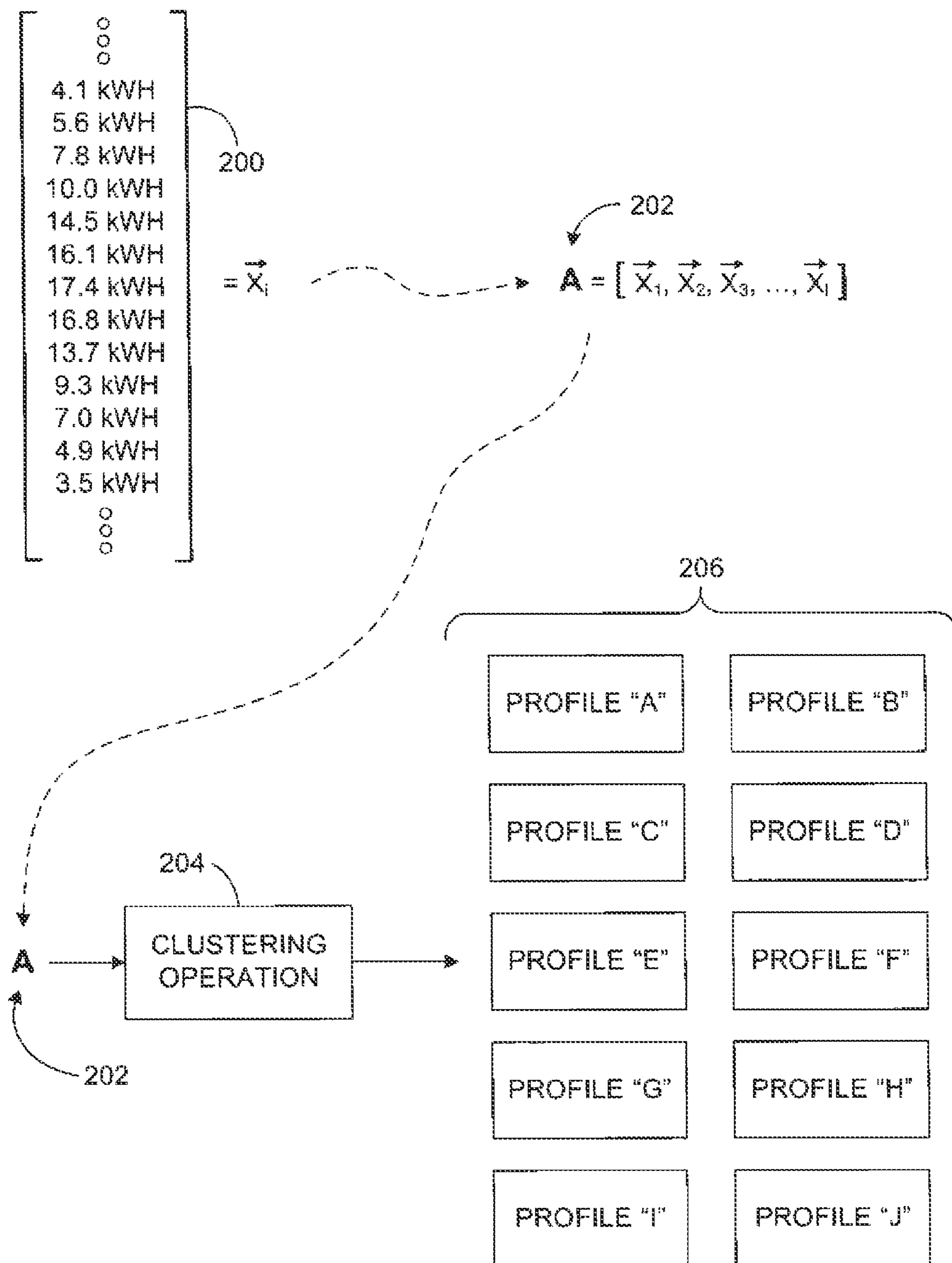


FIG. 2

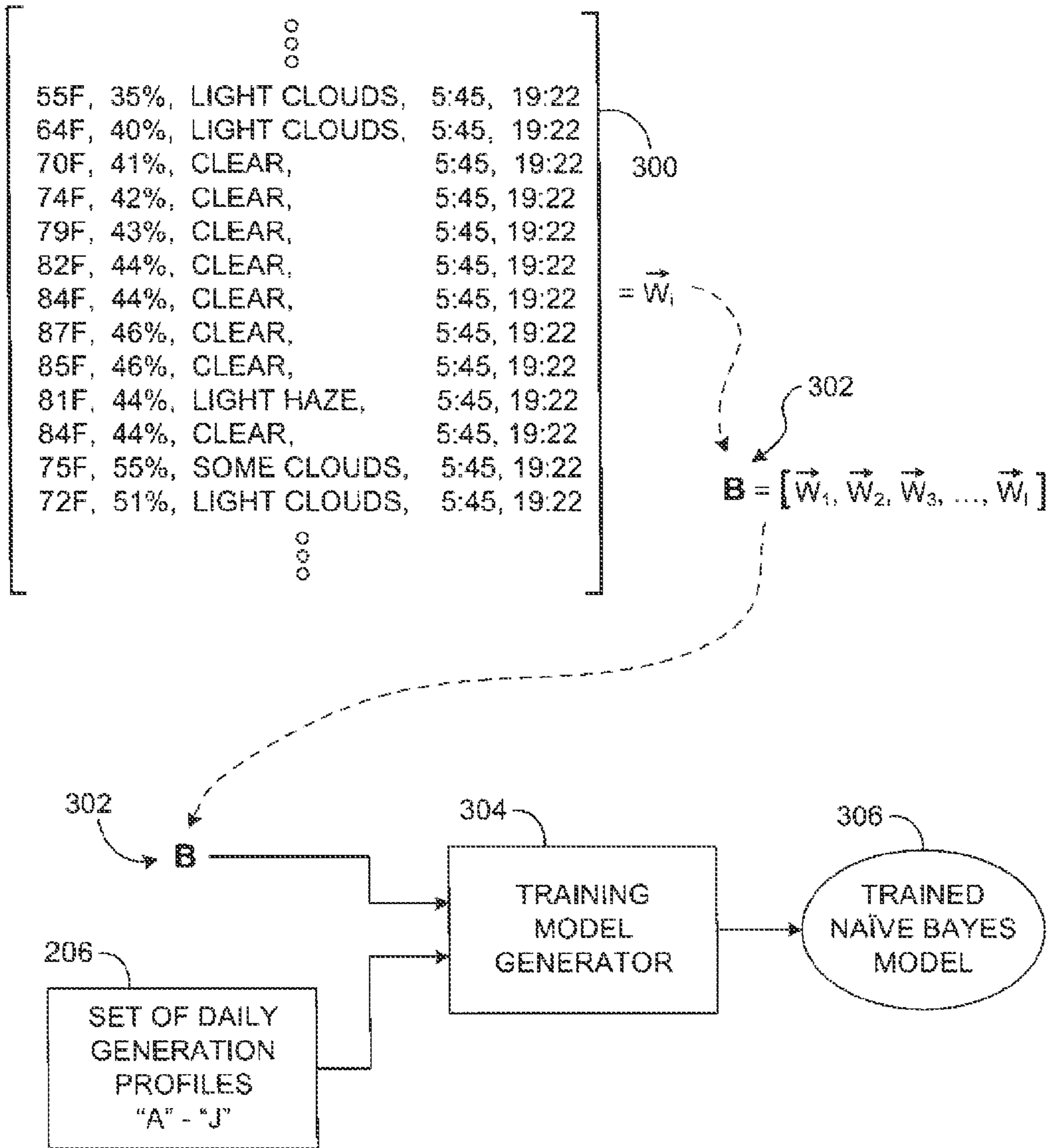


FIG. 3

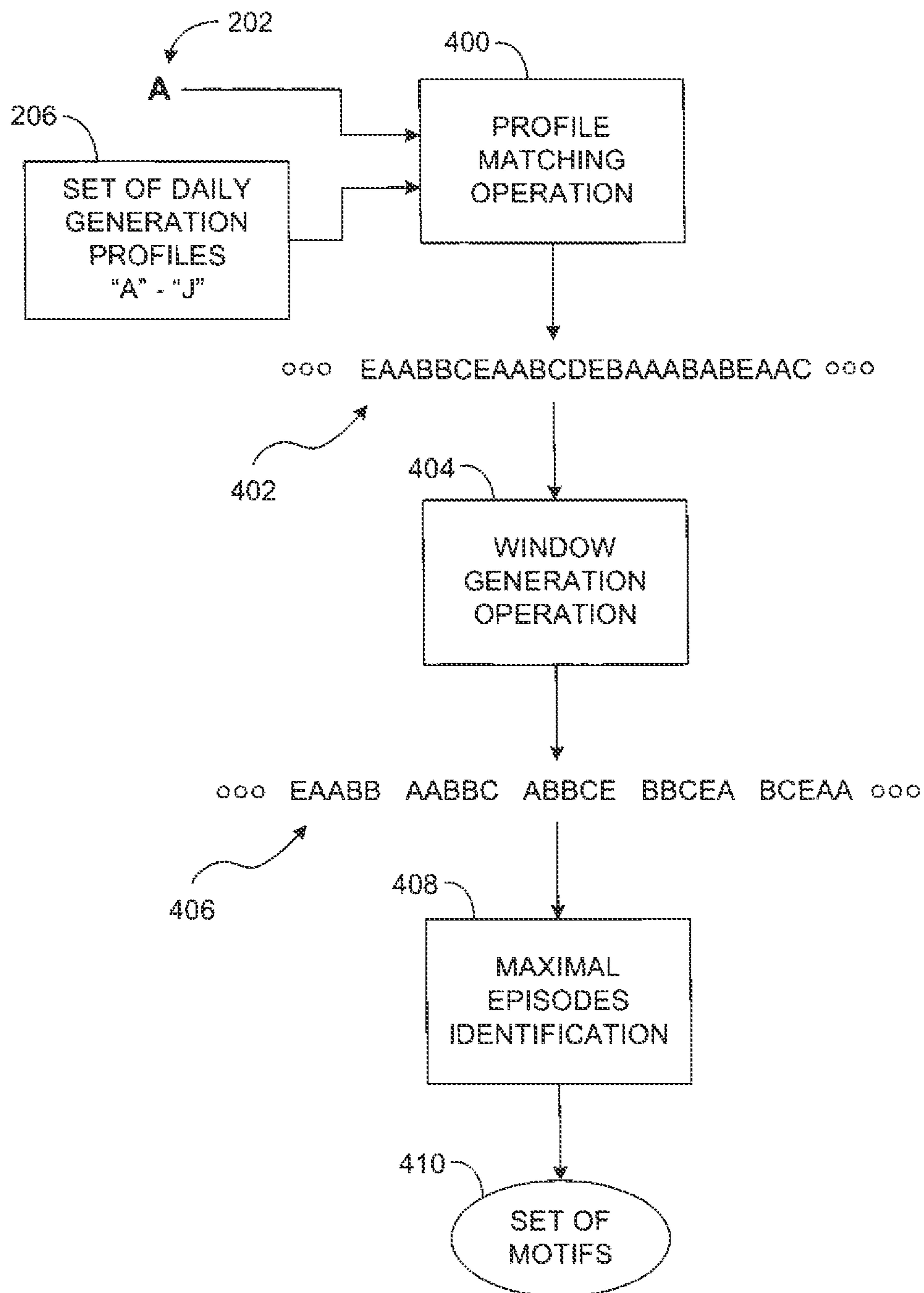


FIG. 4

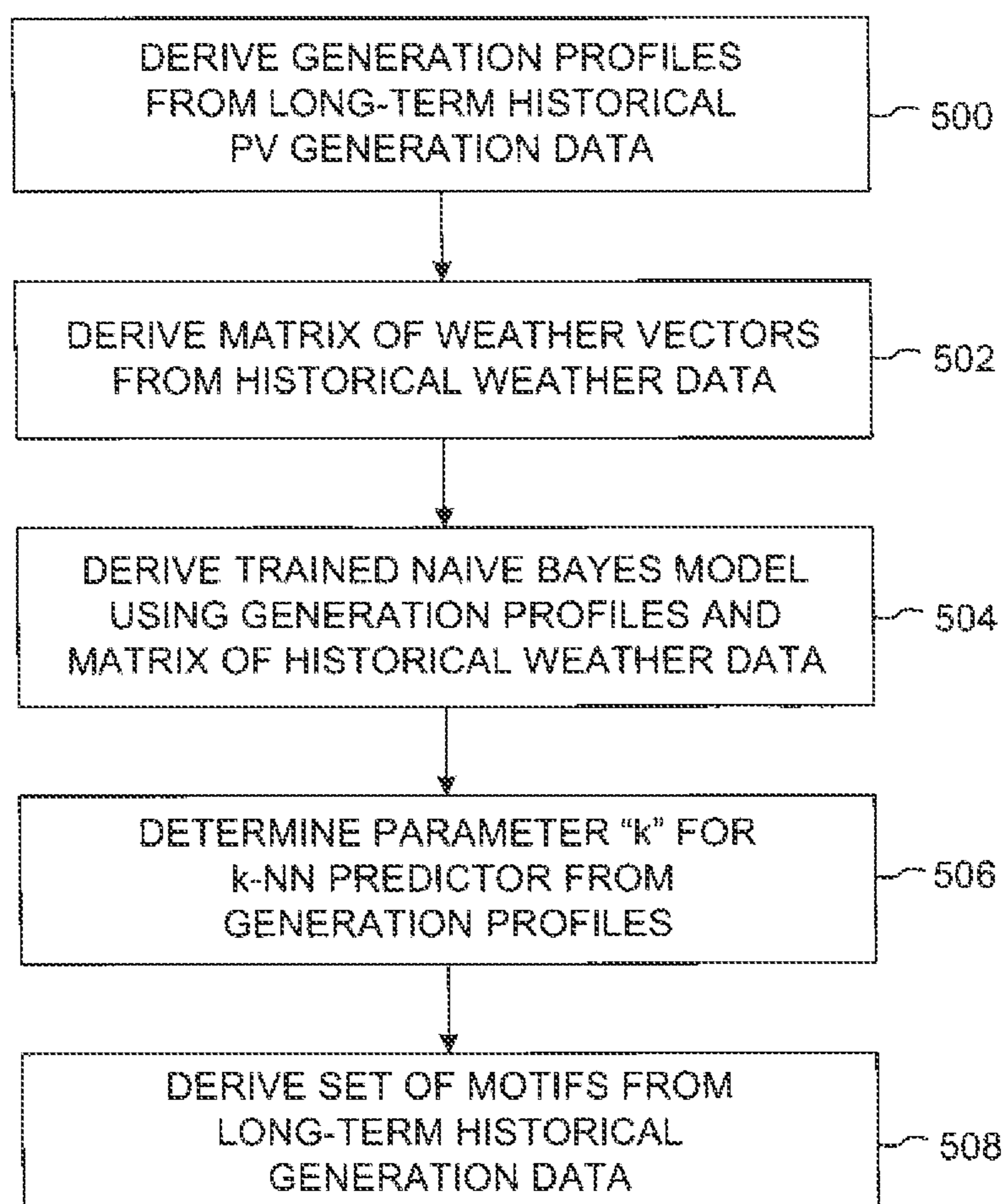


FIG. 5A

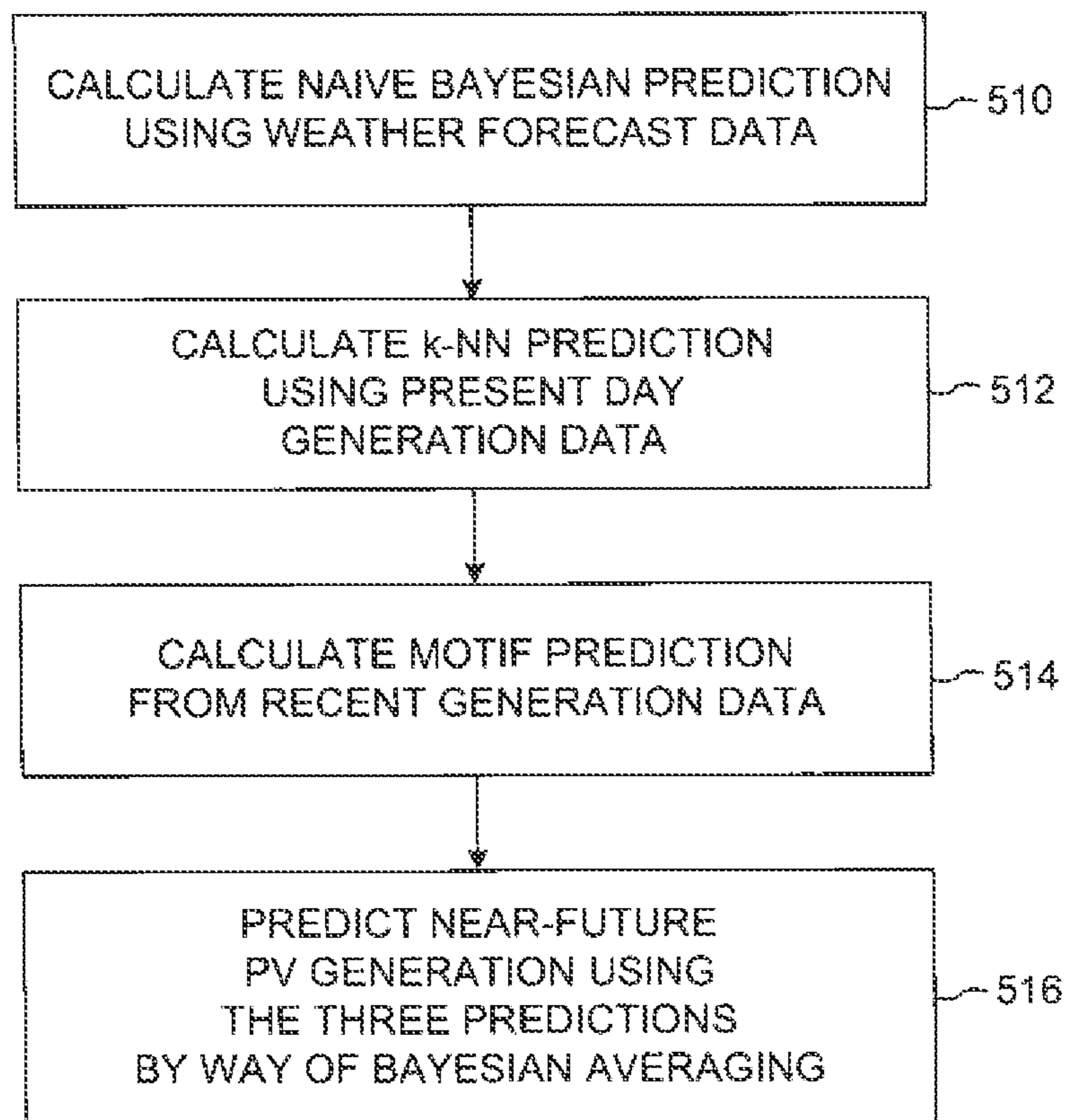


FIG. 5B

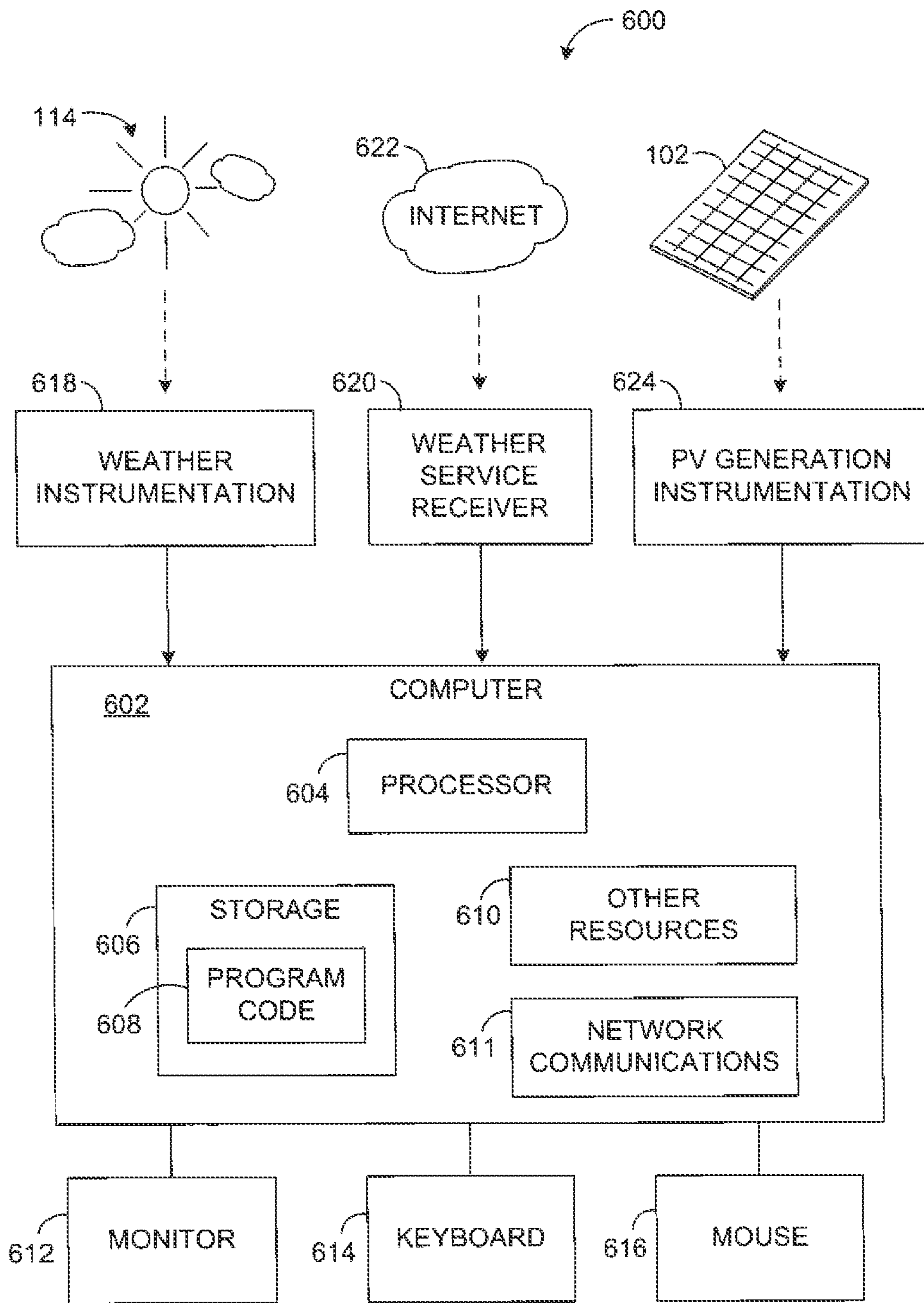


FIG. 6

1

PREDICTING NEAR-FUTURE PHOTOVOLTAIC GENERATION

BACKGROUND

A photovoltaic (PV) system generates electrical energy by direct conversion of incident sunlight or other photonic energy. However, PV electrical output varies significantly in accordance with daylight hours, weather patterns or other sunlight time/intensity factors. Thus, matching PV generation to the needs of a particular load is subject to uncertainty. The present teachings address the foregoing and related concerns.

BRIEF DESCRIPTION OF THE DRAWINGS

The present embodiments will now be described, by way of example, with reference to the accompanying drawings, in which:

FIG. 1 depicts a block schematic diagram of a photovoltaic prediction system according to one example of the present teachings;

FIG. 2 depicts a diagram of illustrative generation data and a process for deriving generation profiles;

FIG. 3 depicts a diagram of illustrative weather data and a process for deriving a trained Bayesian model;

FIG. 4 depicts a process for deriving a set of motifs;

FIG. 5A depicts a flow diagram of a method in accordance with the present teachings;

FIG. 5B depicts a flow diagram of a method that can be performed as a continuation of, or distinct from, the method of FIG. 5A.

FIG. 6 depicts a block schematic diagram of a computer-based system according to another example.

DETAILED DESCRIPTION

Introduction

Systems and automated methods for predicting photovoltaic (PV) power generation are provided. Weather forecast data, and present-day and historical PV power generation data, are provided to respective predictors (i.e., models). The predictors derive weighted predictions that are used to calculate a Bayesian model average. Near-future power generation by the PV system is predicted using the Bayesian model average. Production rates, worker scheduling, hours of operation and other planning decisions can be made in accordance with the predicted near-future power generation.

In one example, a method is performed using a computer, the method including deriving a first weighted prediction using weather forecast data for a present day. The method also includes deriving a second weighted prediction using present day power generation data for a photovoltaic system. The present day power generation data is acquired by way of instrumentation coupled to the computer and to the photovoltaic system. The method also includes deriving a third weighted prediction using recent historical power generation data for the photovoltaic system. The method also includes deriving a Bayesian model average of at least the first and the second and the third weighted predictions. The method fur-

2

ther includes predicting a near-future power generation by the photovoltaic system using the Bayesian model average.

In another example, a system includes a photovoltaic device, and instrumentation to provide data corresponding to a present power generation of electrical energy by the photovoltaic device. The system also includes a computer to receive the data from the instrumentation. The computer is to derive a prediction of near-future power generation by the photovoltaic device using the present power generation data and recent historical power generation data and weather forecast data.

In still another example, a storage media including a program code, the program code is configured to cause a processor to derive a first weighted prediction using weather forecast data. The program code is also configured to cause the processor to derive a second weighted prediction using present day power generation data for a photovoltaic system. The program code is also configured to cause the processor to derive a third weighted prediction using recent historical power generation data for the photovoltaic system. The program code is further configured to cause the processor to predict a near-future power generation by the photovoltaic system by way of calculating a Bayesian model average of the first and the second and the third weighted predictions.

Profile Discovery

An initial operation contemplated by the present teachings is that of profile discovery, which takes as input the available historical PV power generation data and outputs characteristic profiles. Such profiles can be of any suitable, equal-length time span (e.g., hours, part-day, multiple days, and so on). In an illustrative example, day-long profiles are described. If the actual PV power generation “g” (e.g., kilowatt hours) for each “j-th” hour for an entire “i-th” day is denoted by the vector \vec{X}_i , then such can be written as:

$$\vec{X}_i = \{g_{i,1}, g_{i,2}, \dots, g_{i,J}\} \quad (1)$$

Thus, each day can be defined by a vector \vec{X}_i of up twenty-four dimensions, each dimension being the total electrical power generation value (e.g., kilowatt-hours) for a corresponding hour of that day. The entire PV dataset for “T” days (e.g., one year, one season, or one month) can be expressed as a matrix A as:

$$A = \{ \vec{X}_1, \vec{X}_2, \dots, \vec{X}_T \}^T \quad (2)$$

The dataset, matrix A, is clustered using Euclidean distance between the “J” dimensional feature vectors (i.e., power generation for each day) by k-means (Lloyd 1982) algorithm into “N” clusters. The value of “N” is a parameter in the ensemble method and is estimated by minimizing the cross-validation error of the ensemble, keeping other parameters fixed. This yields “N” day-long profiles D_i . The complete set (matrix) of profiles D is denoted by:

$$D = \{D_1, D_2, \dots, D_N\} \quad (3)$$

and the corresponding set of centroids μ is denoted by:

$$\mu = \{\mu_1, \mu_2, \dots, \mu_N\} \quad (4)$$

This step is required to be run only once on the entire historical PV power generation dataset A. In one example, a total of ten daily power generation profiles are derived. Other suitable sets can also be used.

Naïve Bayesian Predictor

The naïve Bayesian (NB) predictor estimates the mixture coefficients given the weather forecast data, assuming conditional independence of features (it assumed that temperature and humidity follow Gaussian distributions). If all of the training information obtained from the weather-PV table is

3

denoted, such as the likelihood functions and priors of the profiles, by γ (gamma), and the weather forecast by:

$$\rho_{i,j} = \langle \rho_{i,j+1,1}, \rho_{i,j+2,2}, \dots, \rho_{i,j-j,j} \rangle \quad (5)$$

where $\rho_{i,j}$ is the weather forecast ρ at the “j-th” hour of the “i-th” day for the rest of the day. Then, the posterior probability of profile labels, for each remaining time slot, is computed as:

$$Pr(D_n | \rho_{i,j+t,t}, \gamma) \propto (\Pi_k L(D_n | \rho_{i,j+t,t}, [k]) Pr(D_n)) \quad (6)$$

finally giving:

$$Pr(D_n | \rho_{i,j}, \gamma, C_1) = \frac{\sum_{t=1}^{i-j} Pr(D_n | \rho_{i,j+t,t}, \gamma)}{\sum_{n=1}^N \sum_{t=1}^{i-j} Pr(D_n | \rho_{i,j+t,t}, \gamma)} \quad (7)$$

Where C_1 indicates classifier 1.

k-Nearest Neighbor Predictor

The k-nearest neighbor (k-NN) (Dudani 1976) predictor uses prior PV generation during the same day as a feature, and assigns mixing coefficients based on Euclidean distance from centroids of discovered daily profiles. In order to make a prediction at the “j-th” hour of the “i-th” day, for the rest of that day, the already observed PV output values “g” (e.g., kilowatt-hours) for that day:

$$\vec{X}_i(1:j) = \langle g_{i,1}, g_{i,2}, \dots, g_{i,j} \rangle \quad (8)$$

Next, the Euclidean distance of this vector to the truncated centroid vectors (first “j” dimensions) of the PV profiles is found, and the probability of the “i-th” day belonging to a cluster as given by the following equation:

$$Pr(\vec{X}_i \in D_n | \vec{X}_i(1:j), C_2) = \frac{1}{\phi \|\vec{X}_i(1:j) - \vec{\mu}_n(1:j)\|_2} \quad (9)$$

Where ϕ is a normalizing constant found as:

$$\phi = \sum_n \frac{1}{\|\vec{X}_i(1:j) - \vec{\mu}_n(1:j)\|_2} \quad (10)$$

Where C_2 indicates classifier 2.

Motif Predictor

The motif predictor (MP) exploits the sequentiality in PV power generation between successive days to find motifs (i.e., repeated patterns) and to give membership estimates of the daily profiles based on such motifs. For this step, the entire PV power generation data is considered as a stream of profile labels. For non-limiting example, alphabetic letters (labels) “A” through “J” can be assigned where ten respective day-long profiles have been defined. Additionally, a “window size” is defined as: the maximum number “W” of past days that can influence the profile. The stream (i.e., sequential order of labels) as a group of vectors of the form:

$$\langle d_{t-1}, d_{t-2}, \dots, d_{t-W} \rangle \quad (11)$$

Where: $d_j \in (j < t)$ denotes the profile label of the “j-th” day. Varying (or “sliding”) the window of size “W” provides different values of such vectors and the resulting distinct windows can be “mined” for motifs. In one example, window size “W” equals five days. Other suitable window sizes can also be used.

4

The foregoing results in the following definition: For a window W_i ($|W_i|=W$) containing labels $\langle d_{i-W}, \dots, d_{i-2}, d_{i-1} \rangle$, eligible episodes are defined as all such sequences $ep = \langle d_{p1}, d_{p2}, d_{p3}, \dots \rangle$, such that $p_1 < p_2 < p_3 \dots$ (Definition 1).

Definition 1 formalizes the term eligible. As evident from the definition, episodes are allowed to contain gaps. The only criterion is that such episodes must maintain temporal order. Furthermore, an episode ep_1 can be defined to be a sub-episode of ep_2 , denoted by $ep_1 \leq ep_2$, if ep_1 is a sub-sequence of ep_2 .

From the definition of sub-episodes it is evident that if $ep_1 \leq ep_2$, then $ep_1 \notin W_j$ implies that $ep_2 \notin W_j$. That is, the sub-episode property is anti-monotonic. The support of an episode ep_i , denoted by sup_{ep_i} , is equal to the number of windows W_j , such that $ep_i \in W_j$. Finally, a maximal frequent eligible episode can be defined as follows: An eligible episode ep_i is maximal frequent iff: $\text{sup}_{ep_i} > \tau$; and $\nexists ep_j$ such that $ep_i \leq ep_j$ (Definition 2).

An a priori approach (Agrawal and Srikant 1994) can be used to prune out episodes when trying to find the maximally frequent ones (as the relation is anti-monotonic). From the training data set, windows of size “W” are considered and, through a priori counting as in (Patnaik et al. 2011) of the entire corpus maximally frequent episodes (FE) and their corresponding supports are found. Such maximally frequent episodes are referred to herein as motifs. Here τ , the support threshold, is a parameter and this value is estimated through cross-validation keeping the other values constant.

While predicting for the “i-th” day, motifs are sought that contain the “i-th” label (e.g., “A” though “J”) and labels of some of the previous days. For this, the immediately preceding window of size $W-1$ is selected, since the label for the “i-th” day must already be part of the motifs. To find mixing coefficients of profile D_n for the “i-th” day, all those maximally frequent episodes are considered that end with D_n denoted by $ep(D_n)$.

Let us denote the set of all such episodes by $\langle ep(D_n) \rangle = \{ep(D_n)_1, \dots, ep(D_n)_P\}$, where P denotes the number of such episodes in the set. Then, within a window W_i , support of the entire set is given by:

$$\text{sup}(\langle ep(D_n) \rangle) = \sum_p \text{sup}_{ep(D_n)_p} \quad (12)$$

Then, the membership of a profile is given by:

$$Pr(\vec{X}_i \in D_n | \vec{X}_{i-1}, \dots, \vec{X}_{i-W+1}, C_3) = \frac{\text{sup}(\langle ep(D_n) \rangle)}{\sum_{n=1}^N \text{sup}(\langle ep(D_n) \rangle)} \quad (13)$$

Where C_3 indicates classifier 3.

This counting step can be potentially very “expensive” (i.e., significant computing resources may be required to perform the step). However, the inventors have discovered that for the current problem, the best window sizes are small. Through cross-validation, the inventors have selected a window of size 5 days (from the range 3 to 10 days). Hence, the counting step, even if naively implemented, is not too expensive.

Bayesian Model Averaging

The memberships obtained from the three predictors are aggregated and combined to arrive at the final prediction as follows:

$$P(\bar{X}_i \in D_n | D_{i,j} = (\bar{X}_i(1:j), \rho_{i,j}, \bar{X}_{i-1}, \bar{X}_{i-2}, \dots, \bar{X}_{i-w-1})) \quad (14)$$

$$= \sum_{i=1}^3 P(\bar{X}_i \in D_n, C_i | D_{i,j}) \quad (15)$$

$$= \sum_{i=1}^3 P(\bar{X}_i \in D_n | C_i, D_{i,j}) \times P(C_i | D_{i,j}) \quad (16)$$

$$= P(\bar{X}_i \in D_n | C_1, \rho_{i,j}) P(C_1 | D_{i,j}) + \quad (17)$$

$$P(\bar{X}_i \in D_n | C_2, \bar{X}_i(1:j)) P(C_2 | D_{i,j}) P(C_2 | D_{i,j}) +$$

$$P(\bar{X}_i \in D_n | C_3, \bar{X}_{i-1}, \bar{X}_{i-2}, \dots, \bar{X}_{i-w-1}) P(C_3 | D_{i,j})$$

Bayesian Model Averaging (BMA)), as outlined by (Raftery at al., 2005), is used to operate on mutually exclusive parts of the data to computer values of: $P(C_i | D_{i,j})$. BMA is performed in accordance with the fundamental relationship:

$$P(C_i | D_{i,j}) \propto P(D_{i,j} | C_i) \times P(C_i) \quad (18)$$

Assuming a uniform prior for the classifiers, equation (18) above can be written as:

$$P(C_i | D_{i,j}) \propto P(D_{i,j} | C_i) \quad (19)$$

The values of $P(D_{i,j} | C_i)$ can be viewed as the proportion of data explained (truly predicted) when using classifier C_i . This can be estimated by constructing a confusion matrix and taking the relative frequency of true positives as an estimate. It is noted that it is not necessary to assume uniform priors. In at least some cases, the priors are estimated from the data.

Predicted PV Generation Values

Finally, the near-future generation values for the corresponding PV array can be estimated (predicted) as follows:

$$\mathbb{E}(\bar{X}_i(j+1:J) | D_{i,j}) \quad (20)$$

$$= \sum_{\bar{X}_i(j+1:J)} \bar{X}_i(j+1:J) P(\bar{X}_i(j+1:J) | D_{i,j}) \quad (21)$$

$$\sum_{\bar{X}_i(j+1:J)} \bar{X}_i(j+1:J) \sum_{n=1}^N P(\bar{X}_i(j+1:J), \bar{X}_i \in D_n | D_{i,j}) \quad (22)$$

$$= \sum_{\bar{X}_i(j+1:J)} \bar{X}_i(j+1:J) \quad (23)$$

$$\sum_{n=1}^N P(\bar{X}_i(j+1:J) | \bar{X}_i \in D_n) \times P(\bar{X}_i \in D_n | D_{i,j})$$

$$= \sum_n \sum_{\bar{X}_i(j+1:J)} (\bar{X}_i(j+1:J) P(\bar{X}_i(j+1:J) | \bar{X}_i \in D_n)) \times \quad (24)$$

$$P(\bar{X}_i \in D_n | D_{i,j})$$

$$= \sum_n \bar{\mu}_n(j+1:J) P(\bar{X}_i \in D_n | D_{i,j}) \quad (25)$$

Illustrative Parameters

Some heuristics are applied to compute the probabilities of the Bayesian ensemble method. The likelihood needs to be estimated for the classifiers (C_i). In one example, it is assumed that the values $P(D_{i,j} | C_i)$ are dependant only on the hour of the day (i.e., the effect of seasons on classifier beliefs is neglected). Under this assumption, ideally the values need to be estimated for each hour. Instead, a simple heuristic is applied.

In the present example, it is assumed that the data is progressively explained better by the k-NN estimator (C_2), while

the motif predictor, which estimates in a global sense without looking at the data), explains the data in a consistent manner irrespective of the hour of the day. These heuristics are given below:

$$P(D_{i,j} | C_3) = \theta \quad (26a)$$

$$P(D_{i,j} | C_2) = \min(1 - \theta, \alpha \times j + \beta) \quad (26b)$$

$$P(D_{i,j} | C_1) = 1 - \theta - P(D_{i,j} | C_2) \quad (26c)$$

Where all of the values on the left hand side of the equations are bounded between 0.0 and 1.0 during computation. In one or more other cases, the above heuristics are not used, and the probabilities are estimated from the data.

Predictor Training

For all three predictors, or models, in the present example (i.e., NB, k-NN and MP), parameters (including the heuristic combination weights) were selected by training over a range of values and picking the one with least cross-validation error.

The basic daily generation profiles were extracted by k-means clustering over the entire dataset. The number of clusters (i.e., daily generation profiles) were set at 10 based on cross-validation over 5 to 15 clusters. For the motif-based predictor, a threshold support parameter of $\tau=70$ and a window size of 5 were used.

First Illustrative System

Attention is directed now FIG. 1, which depicts a block schematic diagram of a system 100 according to the present teachings. The system 100 is illustrative and non-limiting with respect to the present teachings. Other systems, particular elements, functional entities, operations or combinations thereof can also be defined and used.

The system 100 includes a photovoltaic (PV) array 102. The PV array 102 is defined by a plurality of PV cells (or panels of plural cells each) configured to generate electrical energy by direct conversion of incident sunlight 104. Electrical generation by the PV array 102 is measured and quantified, and corresponding data 106 is used (i.e., formatted) to define present-day power generation data 108. In turn, such data 106 as acquired previously is used to define recent historical power generation data 110. Such recent historical power generation data 110 can be representative of the most recent three days, most recent five days, or any other suitable time span.

The system 100 also includes weather forecast data 112 regarding present and near-future (e.g., next 48 hours) weather conditions 114. In one example, the weather forecast data 112 is acquired from an Internet-based resource, or is aggregated after acquisition from a plurality of respective resources. Weather forecast data 112 can be acquired by way of other suitable sources as well, such as local weather instrumentation, or another suitable source.

The system **100** also includes naïve Bayesian predictor (NBP) **116**. The NBP **116** includes (or uses) a trained naïve Bayesian model to provide a weighted prediction **118** of future electrical generation by the PV array **102** based upon the weather forecast data **112**. In one example, the weighted prediction **118** is scaled and quantified in the range of 0.0 to 1.0. Other scaling factors or prediction formats can also be used. Additional description of the NBP **116** is provided hereinafter.

The system **100** also includes a k-nearest neighbor (k-NN) predictor (NNP) **120**. The NNP **120** uses the present-day power generation data **108** to provide a weighted prediction **122** of future electrical generation by the PV array **102**. In particular, the weighted prediction **122** is derived using electrical generation data observed (or acquired) earlier that same day. In one example, the weighted prediction **122** is scaled and quantified in the range of 0.0 to 1.0, consistent with that of the weight prediction **118**. Other scaling factors or prediction formats can also be used. Additional description of the NNP **120** is provided hereinafter.

The system **100** further includes a motif predictor (MP) **124**. The MP **124** uses the recent historical power generation data **110** to provide a weighted prediction **126** of future electrical generation by the PV array **102**. More particularly, the weighted prediction **126** is derived using repeating patterns or “motifs” identified within an historical sequence of daily electrical generation profiles for the PV array **102**. In one example, the weighted prediction **126** is scaled and quantified in the range of 0.0 to 1.0. Other scaling factors or prediction formats can also be used. Additional description of the MP **124** is provided hereinafter.

The system **100** also includes a Bayesian model averaging (BMA) functionality **128**. The BMA **128** calculates a Bayesian average of the three respective predictions **118**, **122** and **126**, in order to derive a final prediction **130** of near-future electrical generation by the PV array **102**. In one example, the prediction **130** includes (i.e., is formatted to present) a predicted electrical generation profile (e.g., hour-by-hour output) for the remainder of the present day. In another example, the prediction **130** includes a total electrical generation (e.g., kilowatt-hours) for the next day. Other data, formats or granularities can also be predicted.

The system **100** is directed to using weather forecast information, as well as recently observed and historical (respectively) power generation data, in order to predict electrical generation for the near-future for a particular PV array. The system **100** determines or derives the final prediction by way of first determining three respective predictions, which are then used as input to a Bayesian averaging scheme. The particular predictions and the Bayesian averaging are now described in more rigorous detail below.

Illustrative PV Generation Data

Reference is now made to FIG. 2, which depicts photovoltaic power generation data and a process for deriving (i.e., discovering) a set of power generation profiles. The particular data, formatting, sampling intervals (i.e., granularity) and other characteristics are illustrative and non-limiting in nature. Thus, the present teachings contemplate other data and processes having respectively varying characteristics.

An illustrative vector **200**, also identified as vector “Xi”, includes hourly power generation data for a PV array (e.g., **102**). As depicted in the example in FIG. 2, the vector **200** includes thirteen distinct data values (dimensions) in units of kilowatt-hours (kWh), each representing an electrical generation total for a respective hour (e.g., 6 AM to 6 PM local time). However, the data vector **200** is understood to include a total of twenty-four hourly data values. Null or zero values, such as

those corresponding to night-time hours, are not depicted in the interest of clarity, and can optionally be ignored during further data processing. The vector **200** is also referred to as a daily power generation vector for purposes herein.

The vector **200** is aggregated with other respective daily power generation vectors to define a power generation matrix **202**, also identified as matrix “A”. In one example, the power generation matrix **202** includes daily power generation data for an entire year. Other data quantities (time spans) can also be used. As such, the power generation matrix **202** represents long-term historical power generation data for a corresponding PV array.

The generation matrix **202** is then subjected to a clustering operation **204** so as to derive multiple distinct daily generation profiles **206** (ten distinct profiles are illustrated in FIG. 2). The generation profiles are alphabetically labeled as “A”, “B”, “C”, “D”, “E”, “F”, “G”, “H”, “I” and “J”, respectively. Other suitable numbers of daily generation profiles (defining a set) can also be derived or used. In one example, the clustering operation **204** is performed in accordance with the Profile Discovery described above. Other suitable clustering operations can also be used.

Each of the daily generation profiles (profiles) **206**, “A”-“J” respectively, characterizes hourly electrical generation for the PV array for a time span of twenty-four hours or less. For example, time spans of twelve hours, sixteen hours, and so on, can be used in accordance with the maximum daylight hours for a particular PV array location, provided that all of the profiles **206** within a given set are formatted to the same time span.

The profiles **206** collectively represent a set of distinct patterns or templates that can be individually compared to the actual electrical generation of a particular day in a “nearest fit” or “closest match” manner. For example, the actual hourly electrical generation for a given day might be best represented by the profile “B”, while the generation of another day is best represented by the profile “F”, and so on.

Illustrative Weather Data

Reference is now made to FIG. 3, which depicts weather data and a process for deriving a trained naïve Bayesian model. The particular data, formatting, sampling intervals (i.e., granularity) and other characteristics are illustrative and non-limiting in nature. Thus, the present teachings contemplate other data and processes having respectively varying characteristics.

An illustrative vector **300**, also identified as vector “Wi”, includes hourly weather data for a particular day. As depicted, the vector **300** includes thirteen dimensions, each dimension including present air temperature in degrees Fahrenheit, relative humidity in percent, one of several predefined weather condition descriptors, time of sunrise for that day, and time of sunset for that day. Entries corresponding to night-time hours are not depicted in the interest of clarity, and can optionally be ignored during further data processing. However, the data vector **300** is understood to include a total of twenty-four hourly data values. The vector **300** is also referred to as a historical weather vector for purposes herein. Present weather data can also be formatted in the same way.

The vector **300** is aggregated with other respective daily weather vectors to define a weather matrix **302**, also identified as matrix “B”. In one example, the weather matrix **302** includes daily weather data for an entire year. Other data quantities (time ranges) can also be used. Thus, the weather matrix **302** is also referred to as long-term weather data.

The weather matrix **302** and the set of daily generation profiles **206** are then input to a training model generator **304** so as to derive a trained naïve Bayesian model (TNBM) **306**.

In one example, the training model generator **304** operates in accordance with the Predictor Training described above. Other suitable training operations can also be used. The TNBM **306** is then used thereafter as a naïve Bayesian predictor (e.g., **116**) to provide a corresponding prediction (e.g., **118**) in accordance with weather forecast data (e.g., **112**) provided as input thereto.

Illustrative Motif Set Derivation

Reference is now made to FIG. **4**, which depicts a process for deriving (i.e., discovering) a set of motifs (repeating patterns) for historical PV power generation data. The particular data, formatting, and other characteristics are illustrative and non-limiting in nature. Thus, the present teachings contemplate other data and processes having respectively varying characteristics.

The generation matrix **202** and the set of daily generation profiles **206**, respectively described above, are subject to a profile matching operation **400**. The profile matching operation **400** compares each day's electrical generation, as provided by the generation matrix **202**, with the respective profiles "A"-**"J"** so to derive an historical sequence **402** of daily generation profiles. The sequence **402** thus represents the "best approximation" of the daily electrical generation (for the corresponding PV array), in chronological order, for one year. The historical sequence **402** is thus depicted as a stream of alphabetic labels, accordingly.

The historical sequence **402** is now subject to a window generation operation **404**, which parses the historical sequence **402** into distinct windows **406** of uniform length. As depicted, the windows **406** are all five days each. Other suitable window lengths can also be used.

The windows **406** are then subject to maximal episodes identification **408**, which operates to identify repeating patterns within the windows **406**. Repeating patterns (or individual motifs) are correspondingly ranked based on frequency of occurrence and a hierarchical set of such motifs **410** is derived. The set of motifs **410** is used by a motif predictor (e.g., **124**) to provide a corresponding prediction (e.g., **126**) in accordance with recent historical power generation data (e.g., **110**). As a non-limiting example, such a motif predictor might provide a prediction based upon the most recent five days of PV bower generation data. Other suitable uses or operations can also be performed.

Illustrative Methods

Attention is turned now to FIGS. **5A** and **5B**, which depict flow diagrams of respective methods in accordance with the present teachings. The methods of FIGS. **5A-5B** depict particular steps and orders of execution. However, other methods including other steps, omitting one or more of the depicted steps, or proceeding in other orders of execution can also be defined and used. Thus, the present teachings contemplate other methods that can be respectively varied. Reference is also made to FIGS. **1**, **2**, **3** and **4** in the interest of understanding the method of FIGS. **5A-5B**.

The method of FIG. **5A** is, generally and without limitation, directed to profile discovery and the training of respective predictors. As such, the method of FIG. **5A** can be performed only once, or on an infrequent basis, as a preparation toward making near-future predictions. In turn, the method of FIG. **5B** is, generally and without limitation, used in making near-future PV generation predictions by way of the profiles and predictors derived by way of the method of FIG. **5A**. Thus, the method of FIG. **56** can be performed as a continuation of, or repeatedly and distinct from, the method of FIG. **5A**.

At **500**, power generation profiles are derived from historical PV power generation data. For purposes of an illustrative

example, a plurality of distinct daily power generation vectors **200** are aggregated to define a long-term historical bower generation matrix **202**, including one year of power generation data for a particular PV array **102**. The matrix **202** is then subject to a clustering operation **204** resulting in the derivation of ten distinct daily power generation profiles **206**, labeled "A" through "J", respectively. Such an operation is performed by, or using, a computer.

At **502**, a matrix of weather vectors is derived from historical weather data. Continuing the present example, a plurality of daily weather vectors **300** are aggregated to define a weather matrix **302**, representing one year of weather data for the location of the PV array **102**. A computer is also used to perform step **502**.

At **504**, a naïve Bayesian model is trained using the generation profiles and the historical weather matrix. In the present example, the daily generation profiles **206** and the weather matrix **302** are provided to a training model generator **304**. A computer embodies the model generator **304** that performs the calculations and/or data processing as required to generate a trained naïve Bayesian model **306**. That is, a computer operating according to a program code performs the steps needed to generate the trained naïve Bayesian model **306**. The trained naïve Bayesian model **306** can then be used by the naïve Bayesian predictor **116**.

At **506**, a parameter "k" is determined for a k-nearest neighbor (k-NN) predictor. In the present example, "k" is determined through cross-validation, using the set of daily generation profiles **206** and the training data. Other appropriate methods can also be used to determine "k". The k-NN predictor **120** can use the parameter "k" in making its respective predictions. This operation is also performed using a computer.

At **508**, a set of motifs is derived from historical power generation data. Within the present example, the matrix of power generation data **202** and the set of power generation profiles **206** are subject to a profile matching operation **400**, resulting in an historical sequence **402** of daily power generation profiles. This sequence **402**, representing a historical year of PV power generation arranged in chronological order, is subject to a window generation operation **404**. The window generation **404** parses (divides, or splits) the sequence **402** into a plurality of windows **406**, each being five days long. The windows **406** are then searched for maximal episodes by an operation **408**, resulting in a set of motifs (i.e., repeating patterns) **410**. A computer is used to perform step **508**.

At **510**, a naïve Bayesian prediction is calculated using present weather data. In the present example, weather forecast data **112** is provided to the naïve Bayesian predictor **116**. The naïve Bayesian predictor **116** uses the trained naïve Bayesian model derived at **504** above to provide a prediction **118** of near-future PV generation. In one example, the prediction **118** is formatted as a weighted value in the range of 0.0 to 1.0. A computer is also used to perform step **510**.

At **512**, a k-nearest neighbor prediction is calculated using present power generation data. In the present example, PV power generation data **108** from earlier the same day (e.g., the immediately previous four hours) are provided to the k-NN predictor **120**. The k-NN predictor **120** compares the present-day power generation data **108** to the daily power generation profiles **206** to derive a prediction **122** of near-future PV bower generation. In one example, the prediction **122** is formatted as a weighted value in the range of 0.0 to 1.0. A computer is also used to perform step **512**.

At **514**, a motif prediction is calculated using recent historical power generation data. In the present example, recent historical power generation data **110** (e.g., the most recent

five days), is provided to the motif predictor **124**. The motif predictor **124** compares this most recent power generation data to the set of motifs **410** derived at **508** above to provide a prediction **126** of near-future PV power generation. In one example, the prediction **126** is formatted as a weighted value in the range of 0.0 to 1.0. A computer is also used to perform step **514**.

At **516**, the three respective predictions are subject to Bayesian model averaging in order to predict near-future PV generation. In the present example, the respective predictions (or weighted values) **118**, **122** and **126** are subject to a Bayesian averaging operation **128** to derive a prediction **130**. The prediction **130** expresses the expected electrical generation, as an hourly profile, for the remaining hours of the present day. A computer is also used to perform step **516**.

Illustrative Computer-Based System

Reference is made now to FIG. **6**, which depicts a block schematic of a computer-based system **600** according to one example of the present teachings. The system **600** is illustrative and non-limiting, and other systems having respectively varying constituencies or operations can also be used according to the present teachings.

The system **600** includes a computer **602**. The computer **602** includes a processor **604** to perform various operations in accordance with a machine-readable program code. The computer **602** also includes a tangible storage media **606** including a machine-readable program code **608**. The media **606** can be variously defined, and non-volatile memory, optical or magnetic media, programmable read-only memory or other suitable media types can be used.

The program code **608** is configured to cause the processor **604** to perform various operations in accordance with the present teachings. Thus, the processor **604** can perform data acquisition, calculations, data processing and other operations toward predicting near-future electrical generation for a corresponding PV array in accordance with the program code **608**.

The computer **602** also includes other resources **610**. The other resources can include any suitable circuitry, elements or constituents as required or desired for normal operations of the computer **602**. Non-limiting examples of such other resources **610** include a power supply, large-scale magnetic storage media, and so on. Other suitable resources can also be used. The computer **602** further includes network communications circuitry **611** to couple the computer **602** in bidirectional digital (i.e., data) communications with the Internet **622**, a local or wide-area network, a wireless network, and so on.

The computer **602** also includes a monitor (i.e., electronic display) **612**, a keyboard **614** and a computer mouse **616**, as are respectively familiar to one having ordinary skill in the computer or related arts. The foregoing elements **612-616** can be used to perform their respective conventional functions, and further elaboration is not germane to understanding the present teachings.

The system **600** also includes weather instrumentation **618**. The weather instrumentation **618** is configured to provide data to the computer **602** regarding present weather **114**. The computer **602** can acquire weather such as temperature, humidity, wind speed, insolation or other factors with any suitable chronological granularity (e.g., hourly, quarter-hourly, and so on). The computer **602** can thus accumulate historical weather information by way of the weather instrumentation **618**.

The system **600** also includes a weather service receiver **620**. The weather service receiver **620** is configured to acquire weather forecast data (e.g., **112**) from the Internet **622** and to

provide that data to the computer **602**. Thus, the computer **602** can derive (or calculate) naïve Bayesian predictions (e.g., **118**) using the forecast data acquired by way of the weather service receiver **620**. Other uses for data or information obtained by way of the weather service receiver **620** can also be performed.

The system **600** also includes PV power generation instrumentation **624**. The PV power generation instrumentation **624** is configured to measure (i.e., meter) electrical production by the PV array **102** and to provide corresponding data to the computer **602**. Instantaneous voltage and current can be measured, and values derived or time-integrated there from (e.g., amp-hours, kilowatt-hours) can thus be acquired and stored. Thus, present day power generation data (e.g., **108**) as well as recent or long-term historical power generation data can be acquired and used by the computer **602** to calculate k-NN predictions (e.g., **122**) and motif predictions (e.g., **126**).

The system **600** generally depicts a computer-based system for implementing the present teachings. Calculations and Bayesian averaging, as well as model training and derivation, and provisions of near-future generation predictions can be performed by the computer **602** in accordance with the present teachings.

In general, the present teachings contemplate systems and methods for making predictions for near-future electrical generation by a photovoltaic array. A plurality of respective predictors, or calculation models, are derived and prepared in accordance with historical weather and power generation data for the particular PV array in question. Three predictor types are described herein, but the present teachings contemplate that other predictors, or any suitable number of such predictors, can also be used. A computer, operating by way of machine-readable program code, can be used to prepare the models, perform calculations, and provide predictions.

In one example, present-day generation, weather forecast information, and recent past electrical generation are used as input data to three respective predictors. Each of the predictors derives or calculates a prediction, or weighted value, regarding near-future generation by the PV array. These values are then subjected to Bayesian averaging to arrive at a single prediction for near-future generation. Such a prediction can pertain to the remaining daylight hours of the present day. Other time spans can also be used.

The prediction can be used in workload or production planning, worker time scheduling, load shedding, or other logistics or operations according to the anticipated electrical production for that PV array. Increased productivity and efficiency, and reduced operating cost and waste, can be achieved accordingly.

In general, the foregoing description is intended to be illustrative and not restrictive. Many embodiments and applications other than the examples provided would be apparent to those of skill in the art upon reading the above description. The scope of the invention should be determined, not with reference to the above description, but should instead be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled. It is anticipated and intended that future developments will occur in the arts discussed herein, and that the disclosed systems and methods will be incorporated into such future embodiments. In sure, it should be understood that the invention is capable of modification and variation and is limited only by the following claims.

What is claimed is:

1. A method performed using a computer, comprising: deriving, by a processor of the computer, a first weighted prediction using a trained naïve Bayesian predictor and

13

using weather forecast data for a present day, wherein the first weighted prediction predicts future electrical generation by a photovoltaic system;

deriving, by the processor of the computer, a second weighted prediction using a k-nearest neighbor predictor and using present day power generation data for the photovoltaic system, the present day power generation data acquired by way of instrumentation coupled to the computer and to the photovoltaic system, wherein the second weighted prediction predicts future electrical generation by the photovoltaic system;

deriving, by the processor of the computer, a third weighted prediction using a motif predictor and using recent historical power generation data for the photovoltaic system, wherein the third weighted prediction predicts future electrical generation by the photovoltaic system;

deriving, by the processor of the computer, a Bayesian model average of at least the first and the second and the third weighted predictions;

predicting, by the processor of the computer, a near-future power generation by the photovoltaic system using the Bayesian model; and

adjusting a number of loads on the photovoltaic system based on the prediction of the near-future power generation for the purpose of workload planning.

2. The method according to claim 1, the weather forecast data acquired by the computer by way of the world wide web.

3. The method according to claim 1, the deriving the first weighted prediction performed by processing the weather forecast data for the present day using the trained naïve Bayesian predictor.

4. The method according to claim 1, the deriving the second weighted prediction performed by processing the present day power generation data using the k-nearest neighbor predictor.

5. The method according to claim 1, the deriving the third weighted prediction performed by processing the recent historical power generation data using the motif predictor.

6. The method according to claim 1 further comprising deriving a plurality of daily generation profiles from long-term historical power generation data.

7. The method according to claim 6 further comprising:

- arranging the daily generation profiles in a historical sequence;
- parsing the historical sequence into a plurality of windows, the windows having equal numbers of the daily generation profiles;
- identifying maximal episodes within the plurality of windows; and
- deriving a motif predictor using the maximal episodes, the motif predictor used to derive the third weighted prediction.

8. A system, comprising:

- a photovoltaic device;
- instrumentation to provide data corresponding to a present generation of electrical energy by the photovoltaic device;
- a computer to receive the data from the instrumentation and to:
 - generate a first weighted prediction of future electrical generation using a trained naïve Bayesian predictor and using the present power generation data;
 - generating a second weighted prediction of future electrical generation using a k-nearest neighbor predictor and using weather forecast data;

14

generating a third weighted prediction of future electrical generation using a motif predictor and using recent historical power generation data;

derive a prediction of near-future power generation by the photovoltaic device using the first weighted prediction, the second weighted prediction, and the third weighted prediction; and

adjusting a number of loads on the photovoltaic device based on the prediction of the near-future power generation for the purpose of workload planning.

9. The system according to claim 8, the computer to receive the weather forecast data by way of an Internet-based resource.

10. The system according to claim 8, the computer to derive a plurality of weighted predictions using the present power generation data and historical power generation data and the weather forecast data, the computer to derive the prediction of near-future power generation by way of a Bayesian model average of the plurality of weighted predictions.

11. The system according to claim 10, the computer to derive at least one of the weighted predictions by way of the trained naïve Bayesian predictor, the motif predictor, or the k-nearest neighbor predictor.

12. A system according to claim 8, the computer including a storage media having a program code, the program code to cause the computer to derive the prediction of near-future power generation.

13. The system according to claim 8, the computer to derive a plurality of daily generation profiles from the historical power generation data.

14. The system according to claim 13, the computer to derive the trained naïve Bayesian model from the historical weather data and the daily generation profiles.

15. The system according to claim 13, the computer to parse a historical sequence of the daily generation profiles into a plurality of equal-length windows, the computer to identify maximal episodes within the plurality of windows so as derive a set of motifs for use by the motif predictor.

16. A non-transitory storage media including a program code, the program code to cause a processor to:

- derive a first weighted prediction using a trained naïve Bayesian predictor and using weather forecast data, wherein the firsts weighted prediction predicts future electrical generation by a photovoltaic system;
- derive a second weighted prediction using a k-nearest neighbor predictor and using present day power generation data for the photovoltaic system, wherein the second weighted prediction predicts future electrical generation by the photovoltaic system;
- derive a third weighted prediction using a motif predictor and using recent historical power generation data for the photovoltaic system, wherein the third weighted prediction predicts future electrical generation by the photovoltaic system;
- predict a near-future power generation by the photovoltaic system by way of calculating a Bayesian model average of the first and the second and the third weighted predictions; and
- adjust a number of loads on the photovoltaic system based on the prediction of the near-future power generation for the purpose of workload planning.

17. The non-transitory storage media according to claim 16, the program code to further cause a processor to:

- derive a plurality of daily generation profiles from long-term historical power generation data for the photovoltaic system;

15

arrange the daily generation profiles into an historical
sequence;
parse the historical sequence into a plurality of equal-
length windows;
identify maximal episodes within the plurality of windows; 5
and
train the motif predictor using the maximal episodes.

18. The non-transitory storage media according to claim
17, the program code to further cause a processor to train the
naïve Bayesian predictor using historical weather data and 10
the daily generation profiles.

19. The non-transitory storage media according to claim
16, the program code to further cause a processor to acquire
the weather forecast data by way of communication with an
Internet-based resource. 15

* * * * *

16